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VELOCITY MEASUREMENTS IN THE AEDC LOW SPEED WIND TUNNEL (V/STOL) USING A LASER DOPPLER VELOCIMETER

F. H. Smith and J. A. Parsons
ARO, Inc.

July 1970

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FOREWORD

The work reported herein was sponsored by Headquarters, Arnold Engineering Development Center (AEDC), Air Force Systems Command (AFSC), Arnold Air Force Station, Tennessee, under Program Element 65701F, Project 4344, Task 32.

The results were obtained between October 1 and 25, 1969, by ARO, Inc. (a subsidiary of Sverdrup & Parcel and Associates, Inc.), contract operator of AEDC, AFSC, under Contract F40600-69-C-0001. The ARO project number was BC5019, and the manuscript was submitted for publication on March 25, 1970.

This technical report has been reviewed and is approved.

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ABSTRACT

An in-house developed laser Doppler velocimeter (LDV) was used to make velocity measurements in a low speed wind tunnel. The installation and instrumentation are discussed, and velocity profiles obtained with the LDV are compared with those obtained using conventional techniques. A discussion on the factors which affect the accuracy of the LDV and improvements that would be desirable are also included.

CONTENTS

	<u>Page</u>
I. INTRODUCTION	1
II. PRINCIPLE OF THE LASER DOPPLER VELOCI- METER	1
III. DESCRIPTION OF THE PWT LOW SPEED WIND TUNNEL (V/STOL)	2
IV. LASER DOPPLER VELOCIMETER AND INSTRU- MENTATION	3
V. FLOW SEEDING	4
VI. EXPERIMENTAL PROCEDURES	4
VII. ESTIMATE OF LASER DOPPLER VELOCI- METER ACCURACY	5
VIII. RESULTS AND DISCUSSION	6
IX. CONCLUSIONS	7

APPENDIX
IllustrationsFigure

1. Laser Doppler Velocimeter in Forward Scattering Mode.	11
2. Two-Component Laser Doppler Velocimeter	12
3. Intersection of Beams from Two-Component Laser Doppler Velocimeter.	13
4. 40-in. Focal Length Lens in Low Speed Wind Tunnel Plenum Chamber	14
5. Path of the Laser Doppler Velocimeter Beams in the Low Speed Wind Tunnel.	15
6. Instrumentation Block Diagram	16
7. Boundary-Layer Rake	17
8. Location of Laser Doppler Velocimeter Velocity Survey Data.	18
9. Laser Doppler Velocimeter Velocity Survey Data . . .	19
10. Normalized Laser Doppler Velocimeter Velocity Survey Data	20
11. Sinusoidal Boundary-Layer Velocity Variation	21
12. Boundary-Layer Rake Normalized Velocities.	22

<u>Figure</u>	<u>Page</u>
13. Normalized Laser Doppler Velocimeter Boundary-Layer Velocities, $V_\infty = 60$ ft/sec	23
14. Normalized Laser Doppler Velocimeter Boundary-Layer Velocities, $V_\infty = 100$ ft/sec	24
15. Normalized Laser Doppler Velocimeter Boundary-Layer Velocities, $V_\infty = 160$ ft/sec	25
16. Combined Laser Doppler Velocimeter Normalized Velocity Data	26

SECTION I INTRODUCTION

The use of the laser doppler velocimeter (LDV) for making velocity measurements has several advantages over conventional measurement techniques. The LDV does not measurably perturb the flow since the amount of power that is absorbed by the fluid is minute. Measurements can be made in small or inaccessible areas where conventional instrumentation cannot be installed. Point velocity measurements can be made in volumes as small as 10^{-6} cc by using diffraction-limited lenses. The LDV has a linear response over its entire velocity range, and the limit of the velocity measurement is determined only by the frequency limit of the readout instrumentation. The LDV also can be used to measure rapidly varying velocities which are experienced in fully developed turbulence at Reynolds numbers greater than 10^5 (Ref. 1). The most attractive feature of the LDV is its ability to measure a velocity function directly rather than to measure some indirect parameter which is then used to calculate velocity.

The LDV has undergone many refinements since its development in 1964 (Ref. 2) and has been extensively used in laboratory environments. The number of successful applications of the LDV to measure velocity in operational wind tunnels, however, is rather limited. This report presents the results of the application of an LDV to measure velocities in the Low Speed Wind Tunnel (V/STOL) of the Propulsion Wind Tunnel Facility (PWT) at AEDC.

SECTION II PRINCIPLE OF THE LASER DOPPLER VELOCIMETER

The principle of operation of the LDV is based upon the Doppler effect. Quasi-monochromatic radiation from a continuous-wave (CW) laser is used to illuminate the particles in a flow field. These moving particles scatter the radiation at an optical frequency which is the algebraic sum of the incident laser optical frequency and the Doppler shift frequency caused by the particle velocity.

The LDV used in this test was a two-component reference beam unit having self-aligned optics (Ref. 3). The laser beam was divided into two parallel beams with an intensity ratio of 100:1 by means of a

parallel surface beam-splitting block. The more powerful of the two beams was then divided by a second beam-splitting block (set at 120 deg relative to the first block) into two beams with a 100:1 intensity ratio. The resulting three parallel beams have intensity ratios of 1:1:100. The two lower power reference beams are equally spaced from the illuminating or higher power beam and are set at 90 deg to each other forming an isosceles right triangle with the illuminating beam. The three beams are passed through a lens which focuses them to a common point. These beams form an isosceles pyramid in space, and the apex is the focal or measuring volume. Because of the equal beam spacing and the common focal length, both reference beams form an angle θ with the illuminating beam at the focal volume. The measured velocity vectors lie in the plane formed by each reference beam and the illuminating beam perpendicular to the bisector of the angle θ .

The LDV was used in the forward scattering mode whereby the photomultiplier (PM) tubes are aligned with the two lower power beams which have expanded away from the focal volume. This is illustrated in Fig. 1 of the Appendix. The particles moving through the focal volume scatter radiation stemming from the laser source. The scattered radiation, arising from the higher intensity illuminating beam, is precisely aligned with the lower power reference beam radiation since both radiations emanate from a common point (the measuring volume). The PM tube produces a sinusoidal signal which varies at the difference or Doppler shift frequency (f_D). The difference frequency is related to the velocity (V) of the particles moving in the flow by (Ref. 4)

$$f_D = \frac{2nV}{\lambda_0} \sin \frac{\theta}{2} \quad (1)$$

where n is the index of refraction of the flowing medium, λ_0 is the wavelength of the laser radiation, and θ is the angle formed between the LDV illuminating beam and reference beams.

SECTION III DESCRIPTION OF THE PWT LOW SPEED WIND TUNNEL (V/STOL)

The V/STOL pilot tunnel is a continuous flow, closed circuit, atmospheric total-pressure wind tunnel. The flow is generated by a single-stage, fixed-pitch, 67-in.-diam fan driven by a 100-hp electric motor through a variable speed magnetic clutch. The fan speed is controllable from 50 to 1060 rpm, resulting in flow velocities from 20 to 250 ft/sec. The test section is rectangular in shape with dimensions of 30 in. wide by 45 in. high by 72 in. long. The test section is enclosed in a plenum which permits a controllable uniform pressure field to be obtained around the test section. A more complete description of the tunnel may be found in Ref. 5.

A jet fuselage model was installed in the tunnel during this investigation. The model contained an air ejector to simulate a lifting turbojet and was 5 in. square by 30 in. long with a wingspan of 30 in. and chord of 6 in.

SECTION IV LASER DOPPLER VELOCIMETER AND INSTRUMENTATION

The LDV is shown in Fig. 2, and Fig. 3 shows the intersection of the three beams required for the measurement of two velocity components. Two LDV focusing lenses were used in the test, a 40-in. focal length lens and a 108-in. focal length unit comprised of a 5.2- and a 16-in. focal length lens. The 40-in. lens was installed inside the plenum chamber adjacent to the test section as shown in Fig. 4, and the combination lens was mounted external to the plenum chamber.

The plenum chamber of the low speed wind tunnel does not have a window in the far wall. This gave two possible locations for mounting the PM tubes, either in the plenum with the resulting inconvenience of inaccessibility for adjustment or outside the plenum which would require the beams to be reflected through the tunnel. The latter method involved additional losses from air-glass surface reflections but was selected as the better of the two arrangements. A second surface, industrial quality mirror, was mounted in the plenum chamber which reflected the mixed (scattered plus reference) beams back to the photomultiplier tubes mounted adjacent to the LDV illuminating optics. The path of the LDV beams in the Low Speed Wind Tunnel is shown in Fig. 5.

Each PM tube output was fed into a Hewlett-Packard 461A wide-band amplifier and displayed on a Singer SPA-3 spectrum analyzer. The frequency of each displayed signal was determined by superimposing the signal output of a Hewlett-Packard 606A signal generator (oscillator) on the LDV signal and viewing them simultaneously, and visually matching them on the spectrum analyzer. The frequency of the oscillator was then counted on a Hewlett-Packard 5245M frequency counter. The binary coded decimal output of the frequency counter was next processed by a Hewlett-Packard 2515A digital scanner and then by a Hewlett-Packard 5050A digital printer for a permanent record of the frequency. The block diagram of the instrumentation is shown in Fig. 6.

A total-pressure rake was installed to obtain comparative tunnel wall boundary-layer velocities. This rake, shown in Fig. 7, has 21 tubes, and the pressures were read with a 1012-3 Barocel electronic manometer.

SECTION V FLOW SEEDING

The flow seeding, necessary to obtain radiation scattering particles, was accomplished by heating mineral oil, condensing the vapor in a cool airstream, and injecting the residual smoke particles into the tunnel. The seeding was introduced into the tunnel through a probe located in the stilling chamber. The probe was designed so that its insertion depth and angle of attack could be varied with respect to the airflow. However, upon operating the seeding generator with the tunnel, it was found that the position of the seeding probe was not critical. After making several circuits around the tunnel, the seed particles were so uniformly distributed that a velocity signal could be obtained anywhere in the test section regardless of the seeding probe position. The seed particles had a very low decay rate, and adequate seeding could be maintained at a mineral oil input of one fluid ounce per hour. Upon termination of the seeding, measurable signals could still be acquired for about 35 min at a nominal test section velocity of 100 ft/sec.

SECTION VI EXPERIMENTAL PROCEDURES

The installation of the LDV and its traverse was made external to the plenum chamber. The LDV was aligned with respect to the test section so that the axial and the vertical velocity components could be measured. The LDV was mounted on a traverse system which provided horizontal and vertical translation, while the transverse movement of the focal volume was accomplished by means of the lenses. The equipment operation was verified by setting tunnel velocities and varying the flow seeding rates until satisfactory signals could be obtained. Upon completion of the checkout, a flow velocity survey was made in the test section.

The velocity was measured in a plane at tunnel station 24. Data were taken in 1-in. increments as shown in Fig. 8. Also shown are two regions where data could not be taken because of interference from the side wall frame and the model.

The velocity data were taken by setting the LDV elevation relative to the test section bottom wall and adjusting the focusing lens to locate the focal volume at the desired point. The Doppler frequency was matched to the signal generator frequency and the results printed on the digital printer. The survey data were made at a nominal velocity of

100 ft/sec. At the time each LDV data point was taken, the wind tunnel total pressure, static pressure, and total temperature were also recorded.

The vertical velocity component of the tunnel was monitored throughout the survey, but at no time could be resolved on the spectrum analyzer. The operation of the vertical component equipment was verified by locating the LDV focal volume adjacent to the nose of the installed model where the flow was turned and making two component measurements. The lowest vertical velocity measured in this area was 8.48 ft/sec which corresponds to a 7.5-kHz signal. A pure sinusoid signal from an oscillator was put into the spectrum analyzer, and the lowest frequency that could be visually resolved was 50 kHz. This frequency corresponds to a velocity of 6.28 ft/sec. Since the operational signals are not pure sinusoids, the 67.5-kHz signal is considered to be the operational limit of the particular spectrum analyzer used in this test. The vertical velocity components in the tunnel were, therefore, considered to be so small that the resulting signal frequency and amplitude could not be resolved on the spectrum analyzer.

The boundary-layer rake was installed in the test section bottom wall at station 32, 11.12 in. from the near side wall. The boundary layer was measured at velocities of 60, 100, and 160 ft/sec. The LDV and pressure measurements were made at the same location under identical conditions.

SECTION VII ESTIMATE OF LASER DOPPLER VELOCIMETER ACCURACY

The accuracy of these LDV measurements is a function of the following:

1. The ability of the seeding particles to travel at the stream velocity.
2. The accuracy of the measurement of the angle θ between the LDV beams.
3. The size of the focal volume being monitored.
4. The accuracy of locating the focal volume in the flow.
5. The accuracy of visually matching the oscillator frequency display with the Doppler shift frequency display.
6. The accuracy of the frequency counter to measure the oscillator frequency.

It is possible to assign accuracy specification to some of these items while others can only be estimated. Reference 6 gives the results of studies on particle lag and indicates that, under the conditions in the Low Speed Wind Tunnel (V/STOL), the seeding particle velocity to free-stream velocity ratio was greater than 99 percent. However, using 99 percent, this could result in an inaccuracy of 1 ft/sec at a nominal velocity of 100 ft/sec. The angle θ that is formed by the LDV beams gives the greatest source of error as it enters directly into the conversion from frequency to velocity (Eq. (1)). The beam separation in the LDV was measured to ± 0.10 mm. In the LDV-lens combination used for this test, the maximum possible error would be ± 0.6 percent or approximately ± 0.6 ft/sec. Visual matching of signals on the spectrum analyzer has been demonstrated accurate to within ± 0.5 percent or ± 0.5 ft/sec. The accuracy of the counter was -1 count out of 1000 which can be neglected. This gives a maximum velocity measurement error of +1.1 percent, -2.1 percent, or a velocity range of 97.9 ft/sec to 101.1 ft/sec for a 100-ft/sec nominal velocity.

The other two items do not affect the accuracy of the measurement directly. A large focal volume has a greater number of particles passing through it than a small one. The chances of having a velocity variation within the focal volume are, therefore, greater for the larger volume. This velocity variation will have a wider spread of frequencies when displayed on the spectrum analyzer and could contribute some error depending upon the ability of the operator to determine the mean frequency of the display. The magnitude of this error could be on the order of ± 1 percent.

The accuracy of locating the focal volume in the flow is dependent upon the accuracy of the traverse locating readout system. The system used in this test could be read to the nearest $1/32$ in.; therefore, the vertical placement could vary by ± 0.015 in.

SECTION VIII RESULTS AND DISCUSSION

The velocity data obtained in the V/STOL test section are shown for each horizontal traverse in Fig. 9. There is a spread of 3.84 percent in the LDV mean velocity data taken across the surveyed section.

An empirical relationship, determined from the wind tunnel calibration, was used to calculate test section centerline velocity. The velocity data taken with the LDV are shown in Fig. 10 normalized with the test section centerline velocity. The data show a maximum variation of 2.5 percent throughout the area surveyed.

The LDV was used to check the tunnel for steady flow. A comparison of the LDV measured velocity and the tunnel calibration velocity for a 9-min period is shown in Fig. 11. The LDV data indicated a sinusoidal velocity of decreasing amplitude and increasing period, while the calculated velocity indicated an almost constant value. The LDV data were obtained in the boundary layer of the bottom wall, which accounts for the difference in magnitude of the velocities. The effect was not investigated further and could be attributable to aerodynamic or structural characteristics of the tunnel.

The boundary-layer pressure profiles were measured at test section velocities of 60, 100, and 160 ft/sec. Figure 12 shows the velocities, determined by the boundary-layer rake, normalized with the free-stream velocity and plotted versus the height above the bottom wall. The boundary-layer velocity profiles obtained with the LDV are shown in Figs. 13, 14, and 15. The combined plot of the three velocities is shown in Fig. 16. The solid line on the LDV plots is the curve from the boundary-layer rake data, shown for comparison. The LDV boundary-layer survey of Fig. 16 does not exactly match the survey made with the boundary-layer rake. The comparison is excellent at heights of 0.2, 0.3, and 0.4 in. above the tunnel wall. However, at 0.5 in., the LDV measured velocity increases more rapidly than the boundary-layer rake derived velocity. The LDV velocity ratio reaches a value of unity at 1.0 in. above the bottom wall while the rake velocity ratio reaches unity at approximately 1.2 in. These boundary-layer traverses were repeated several times with good repeatability of the data.

SECTION IX CONCLUSIONS

The results of this test show that the LDV is a useful instrument for making point velocity measurements in low speed wind tunnels using existing flow seeding techniques. The flow survey in the wind tunnel indicates that a steady flow with a fairly uniform velocity distribution exists throughout the central portion of the test section. The sinusoidal velocity variation that was measured in the boundary layer of the tunnel bottom wall is unexplained because of the limited data taken. It is not known whether the sinusoid eventually damps out to a negligible level or continues to follow a cyclic pattern.

The accuracy and capability of the LDV could have been improved by the inclusion of a direct data processing system which would eliminate any human error. An improved traversing system would have allowed more accurate location of the focal volume.

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**APPENDIX
ILLUSTRATIONS**

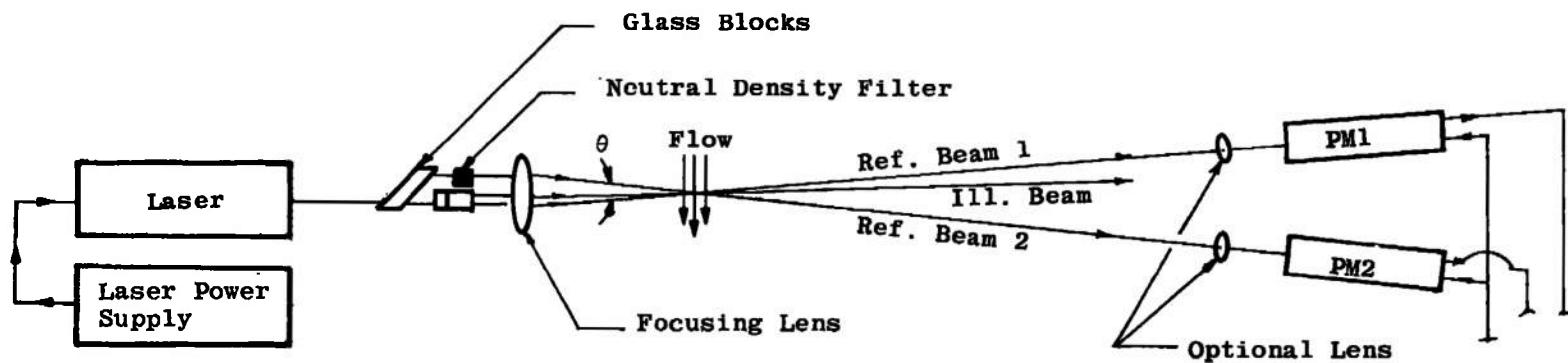


Fig. 1 Laser Doppler Velocimeter in Forward Scattering Mode

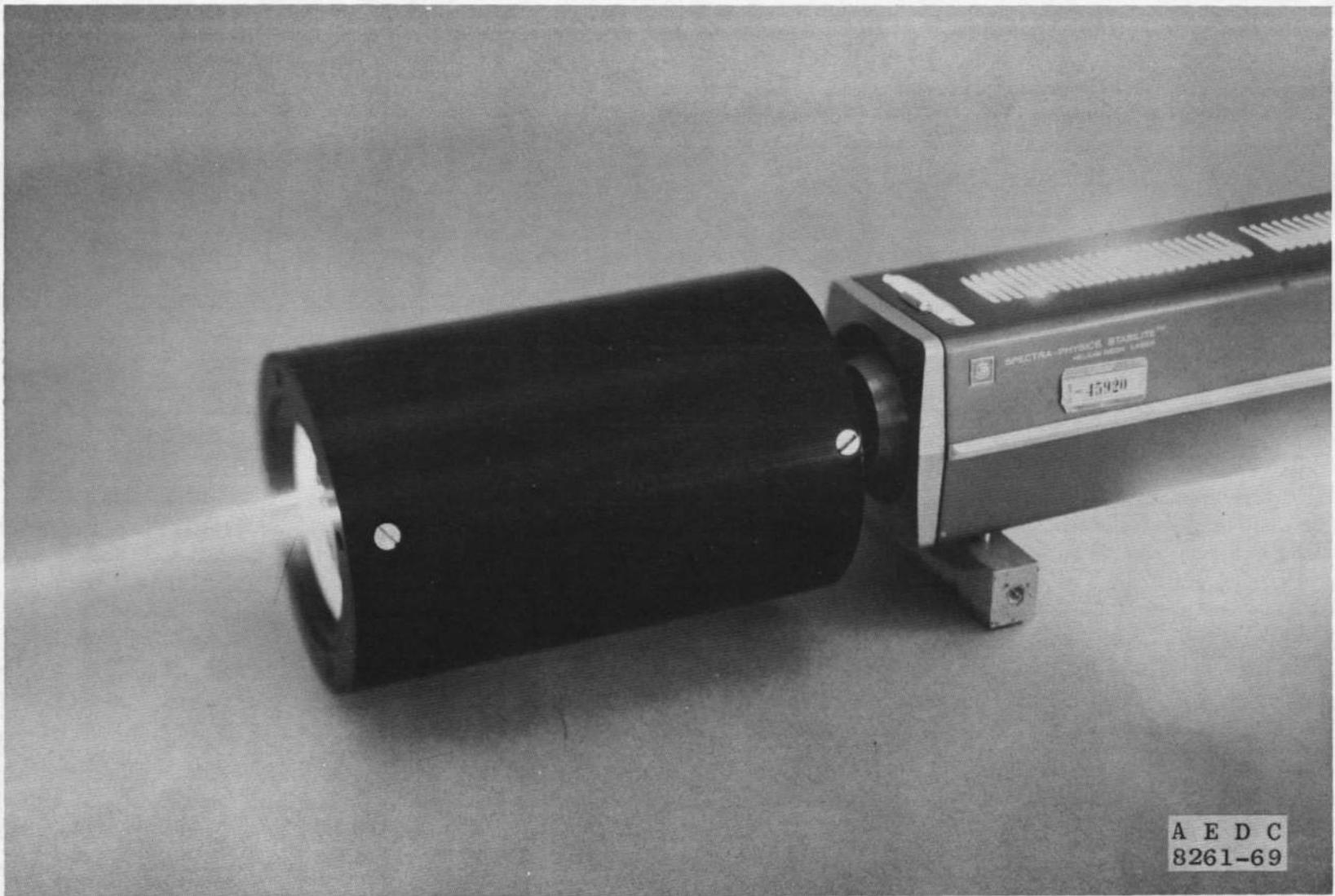


Fig. 2 Two-Component Laser Doppler Velocimeter

13

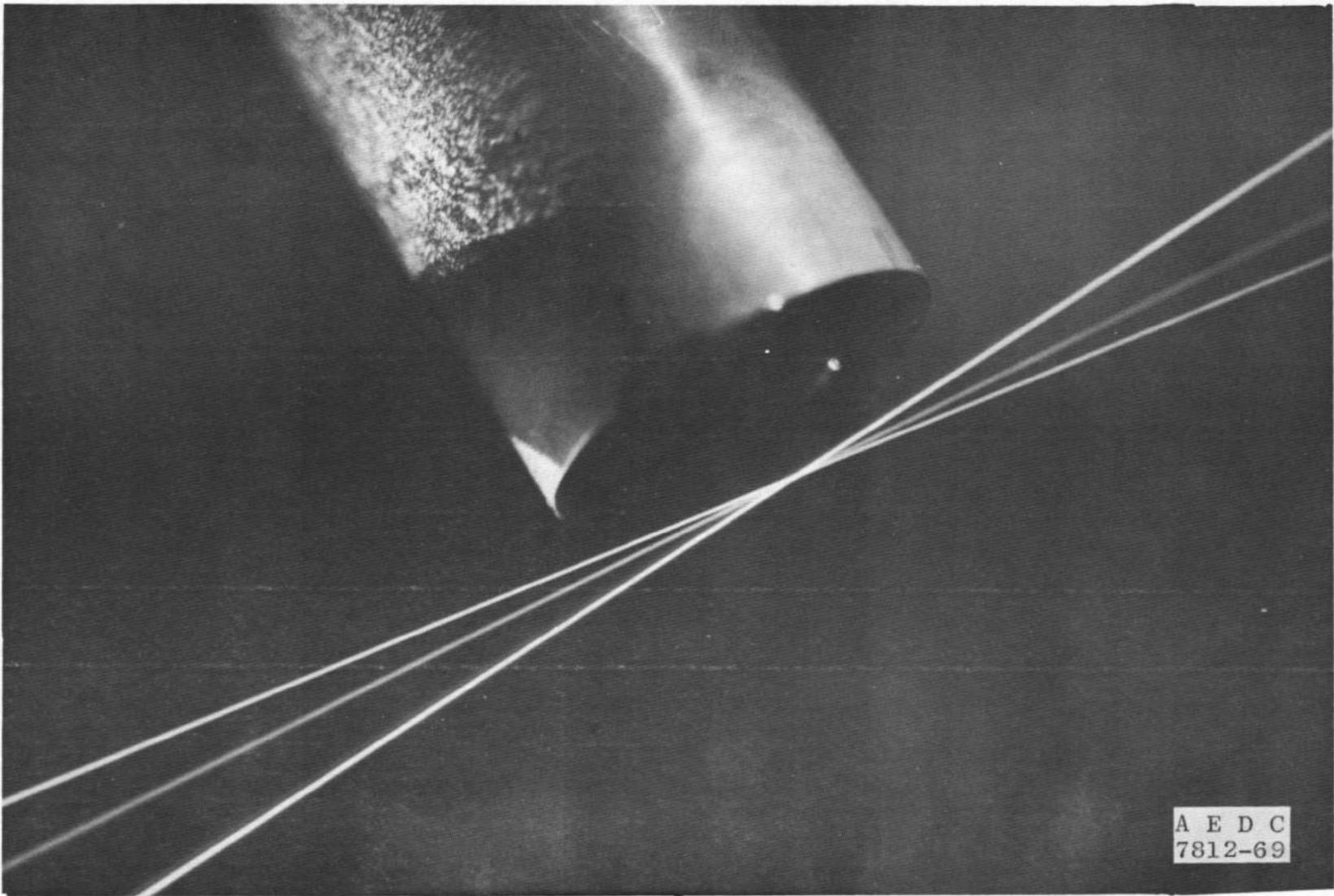


Fig. 3 Intersection of Beams from Two-Component Laser Doppler Velocimeter

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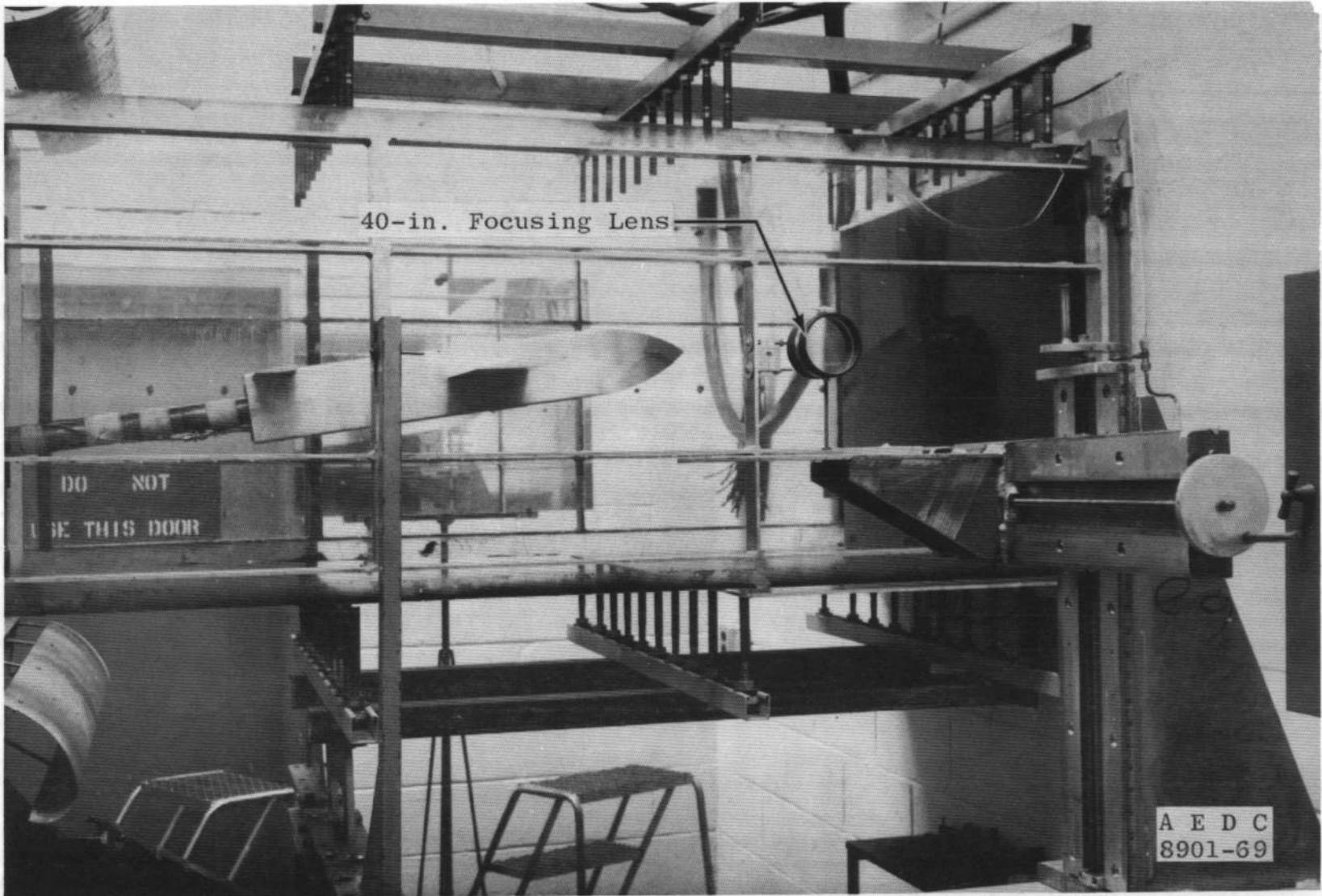


Fig. 4 40-in. Focal Length Lens in Low Speed Wind Tunnel Plenum Chamber

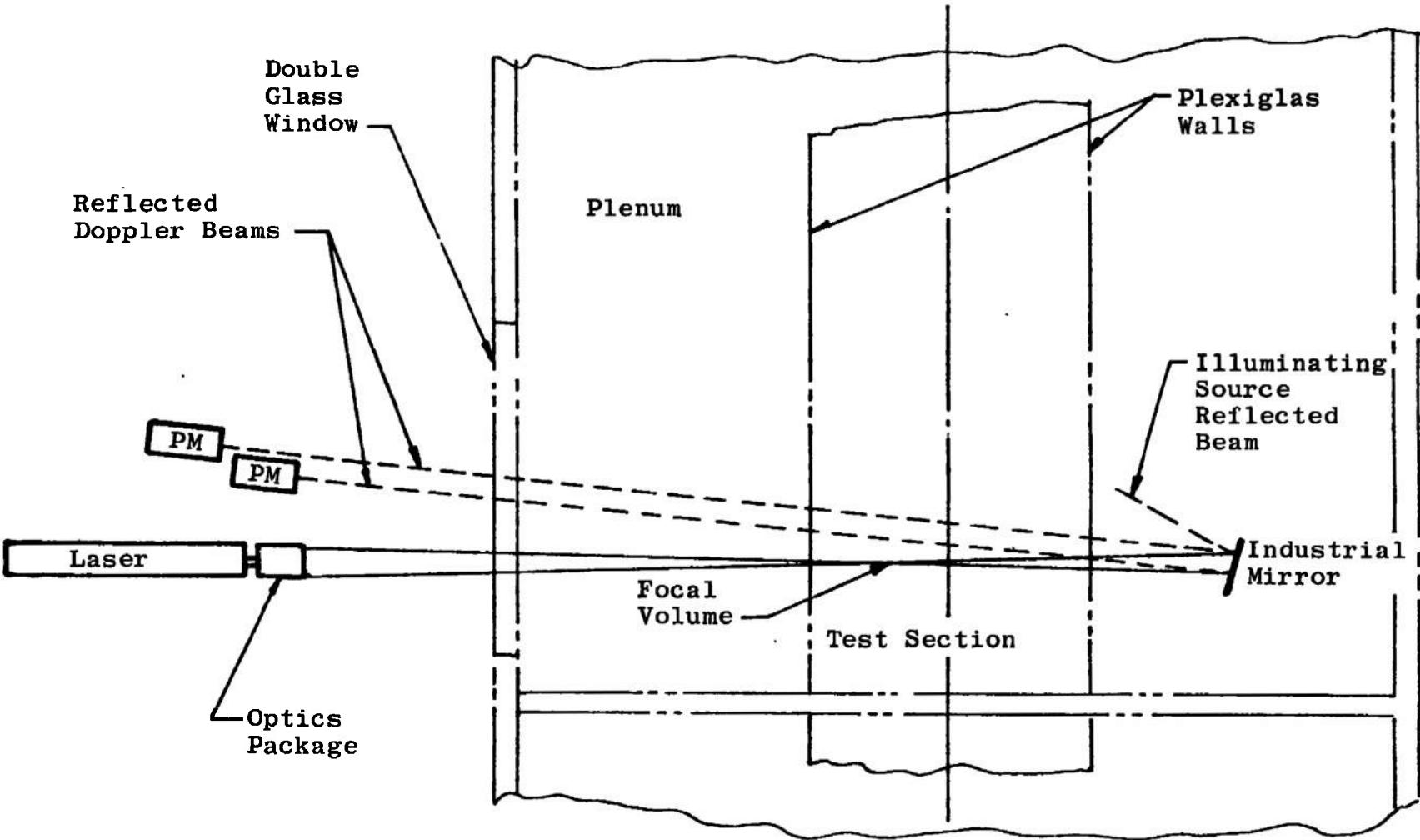


Fig. 5 Path of the Laser Doppler Velocimeter Beams in the Low Speed Wind Tunnel

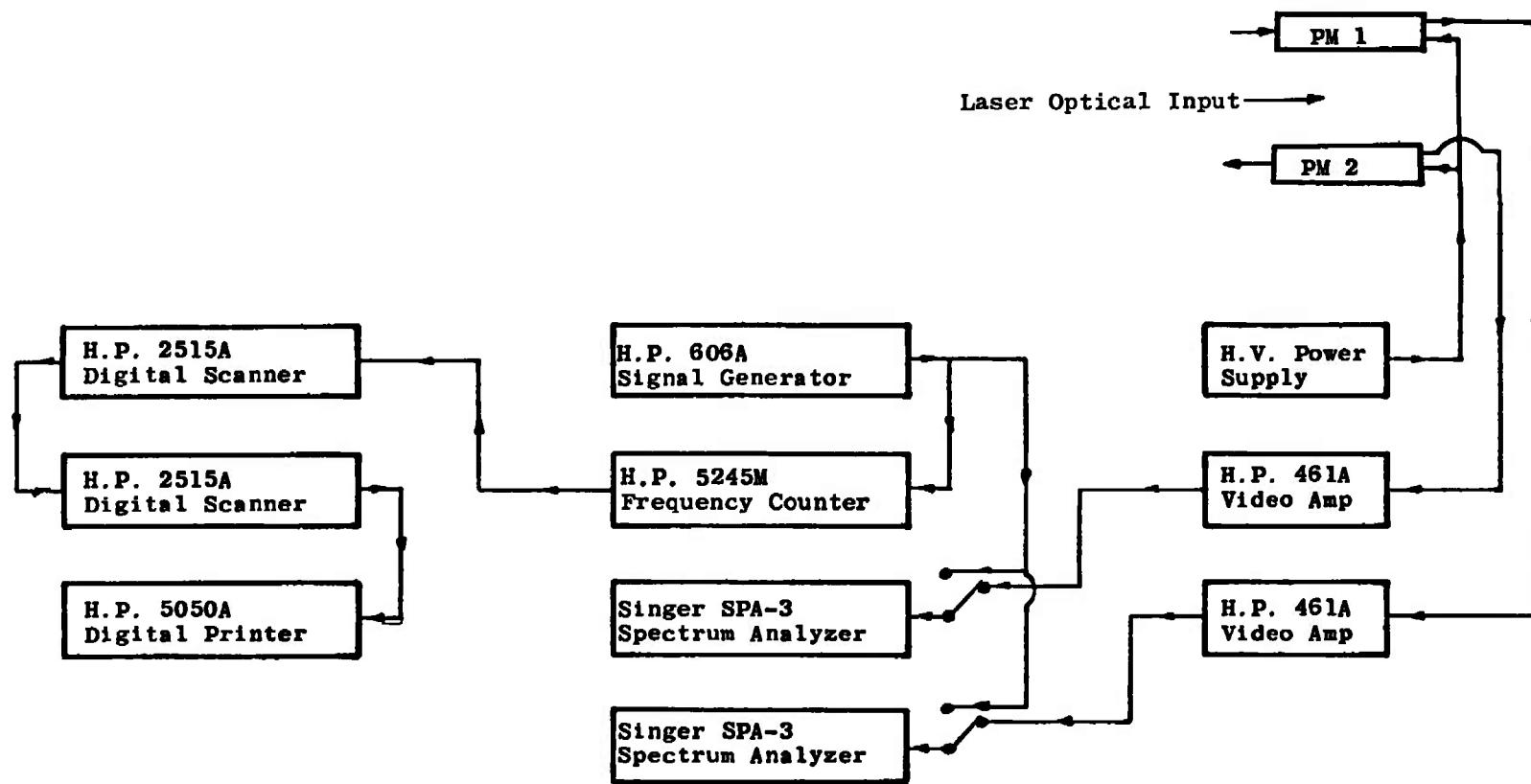


Fig. 6 Instrumentation Block Diagram

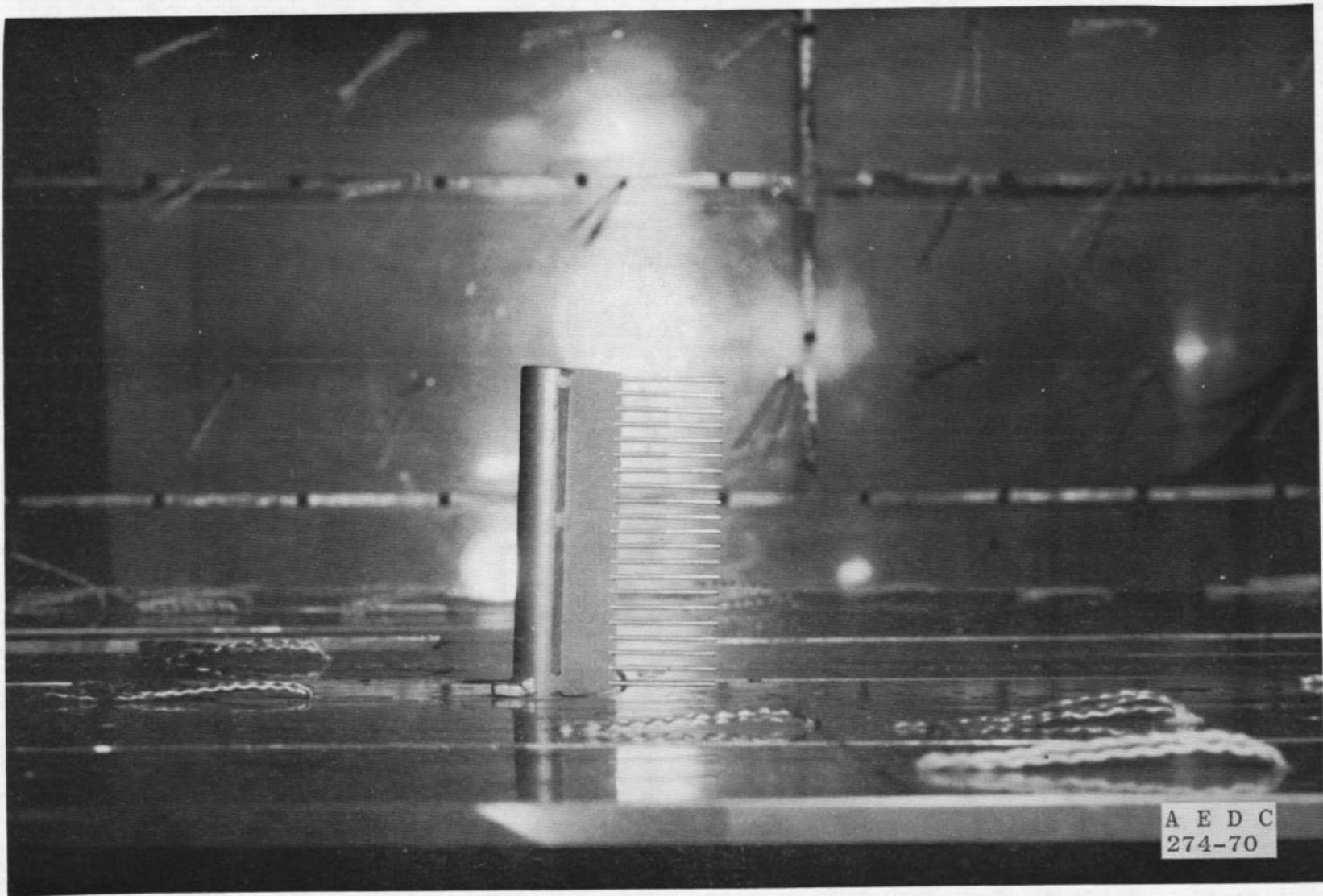


Fig. 7 Boundary-Layer Rake

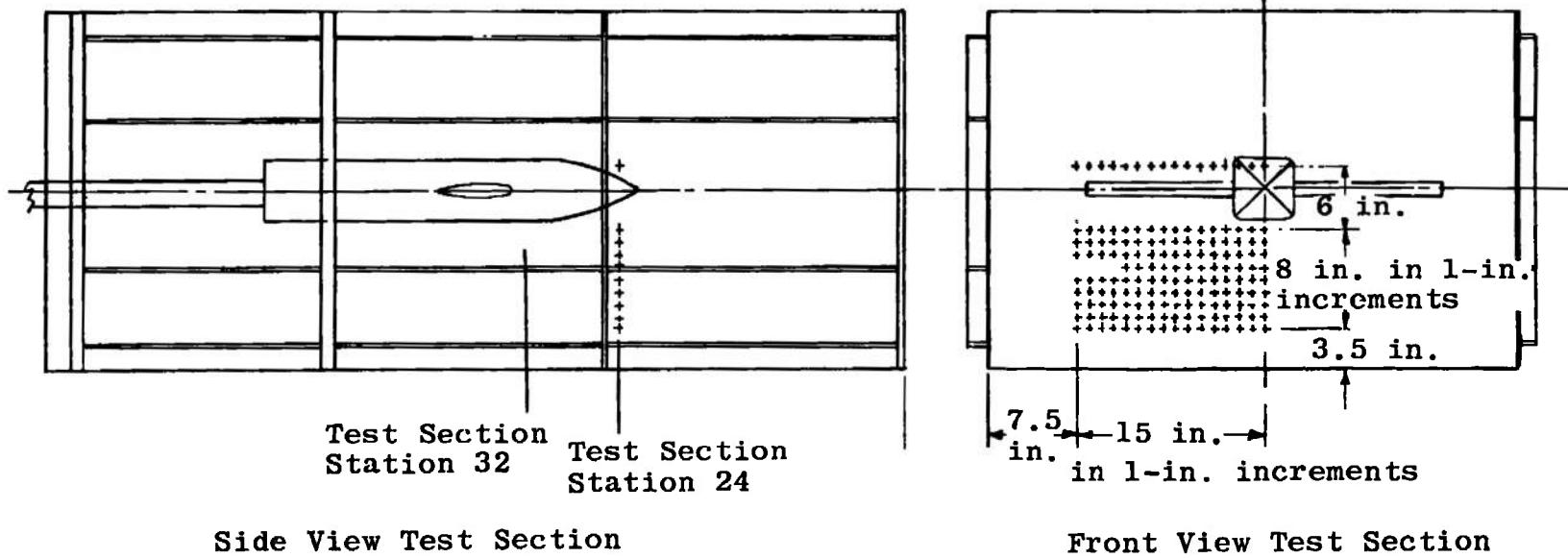


Fig. 8 Location of Laser Doppler Velocimeter Velocity Survey Data

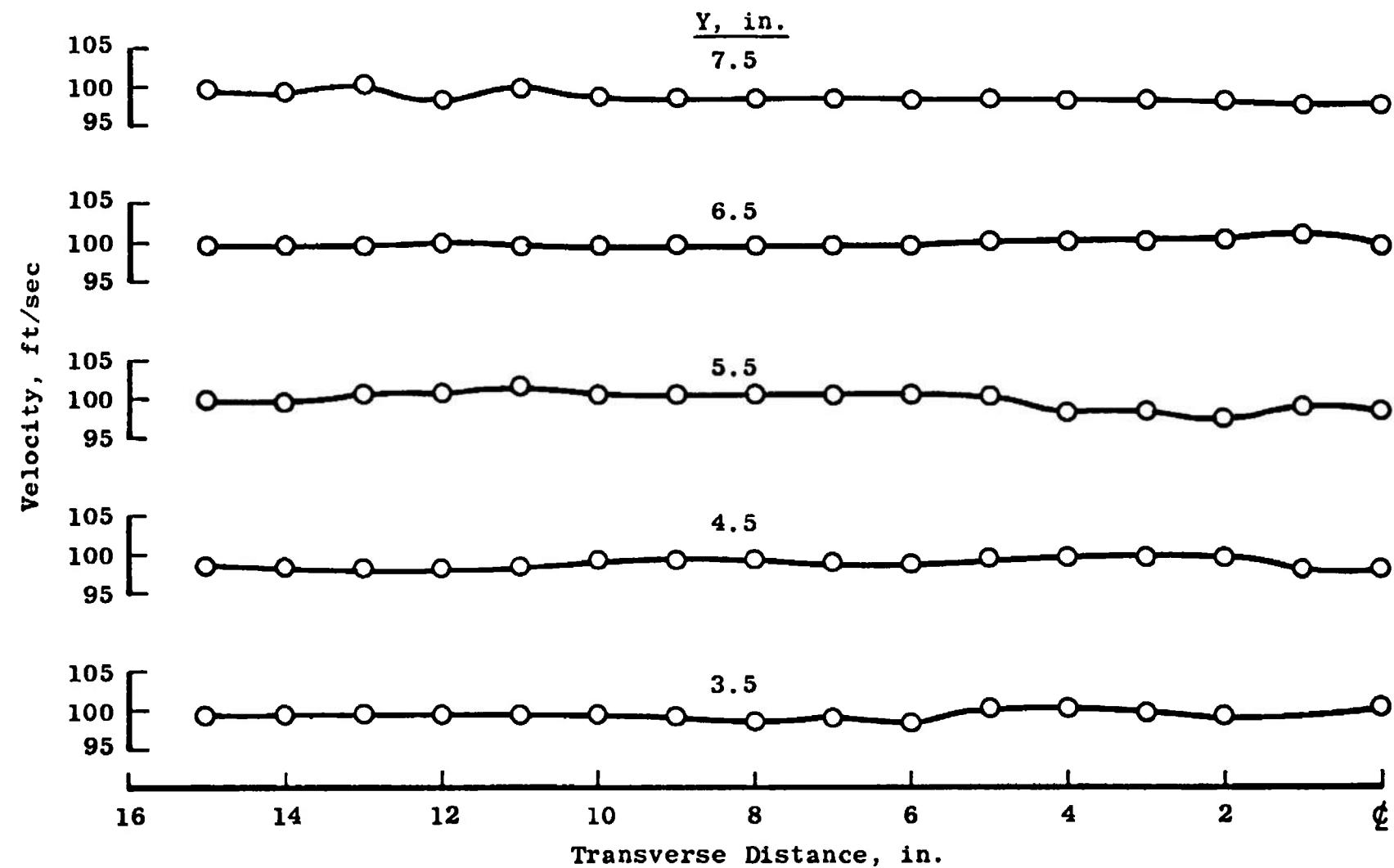


Fig. 9 Laser Doppler Velocimeter Velocity Survey Data

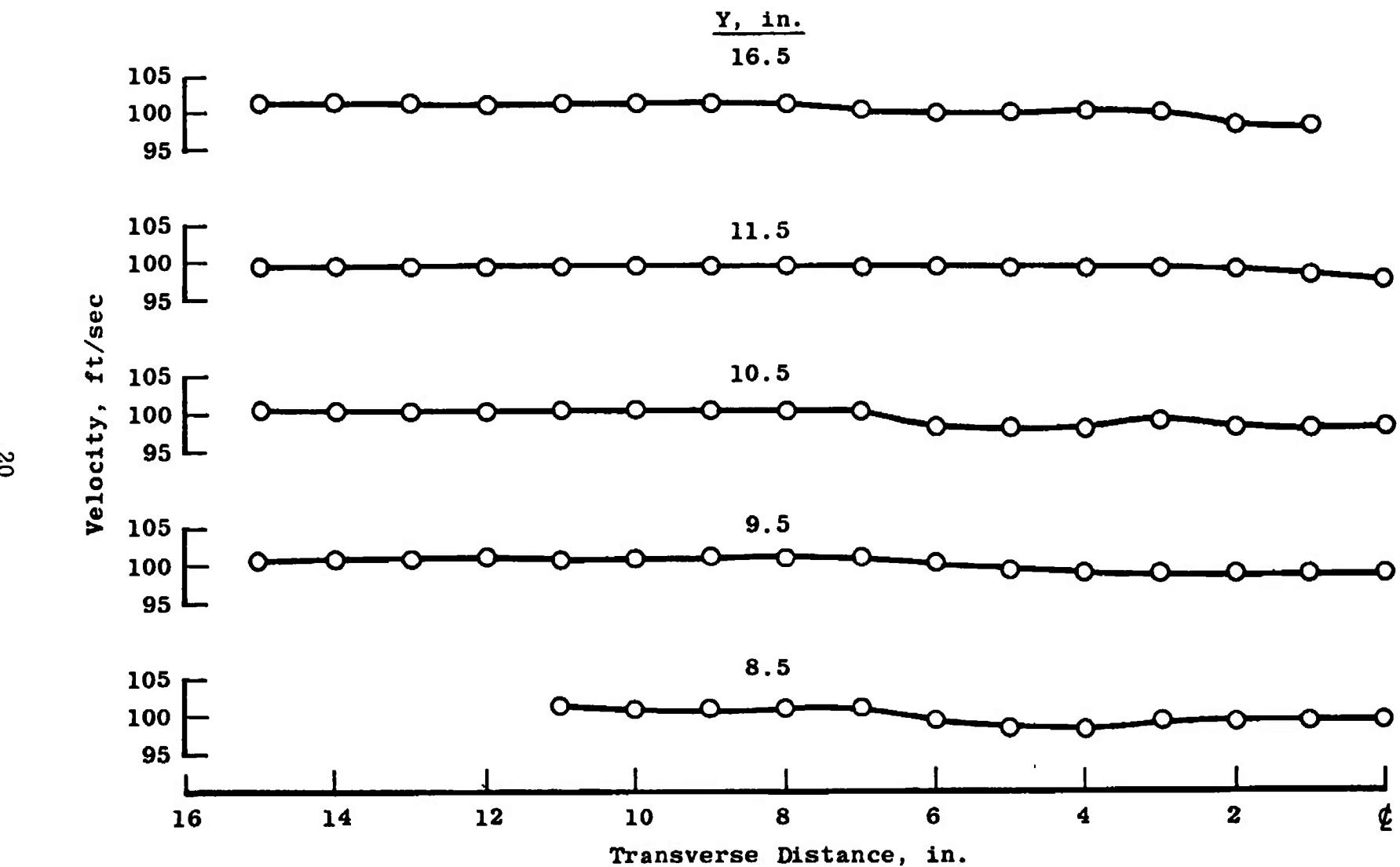


Fig. 9 Concluded

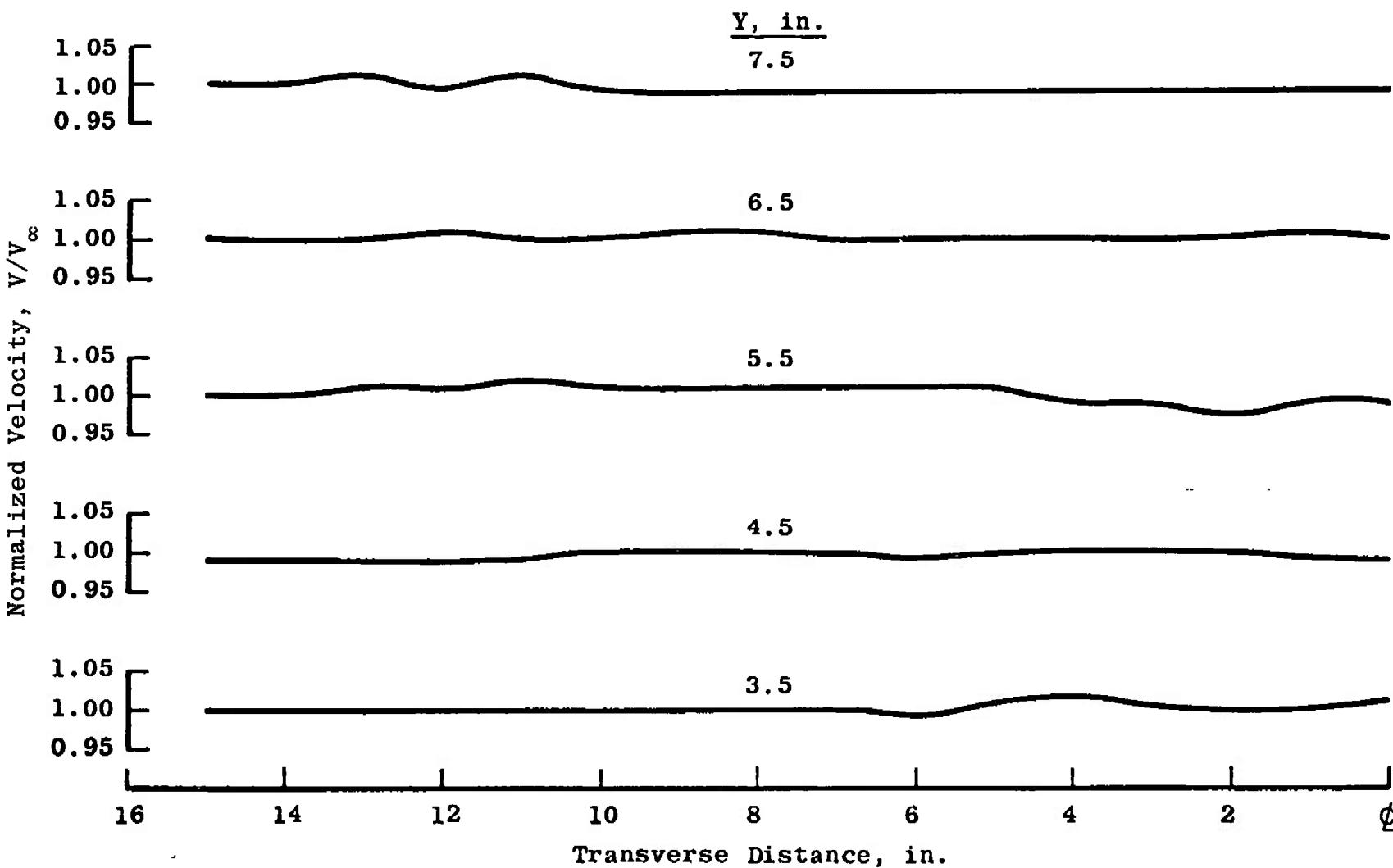


Fig. 10 Normalized Laser Doppler Velocimeter Velocity Survey Data

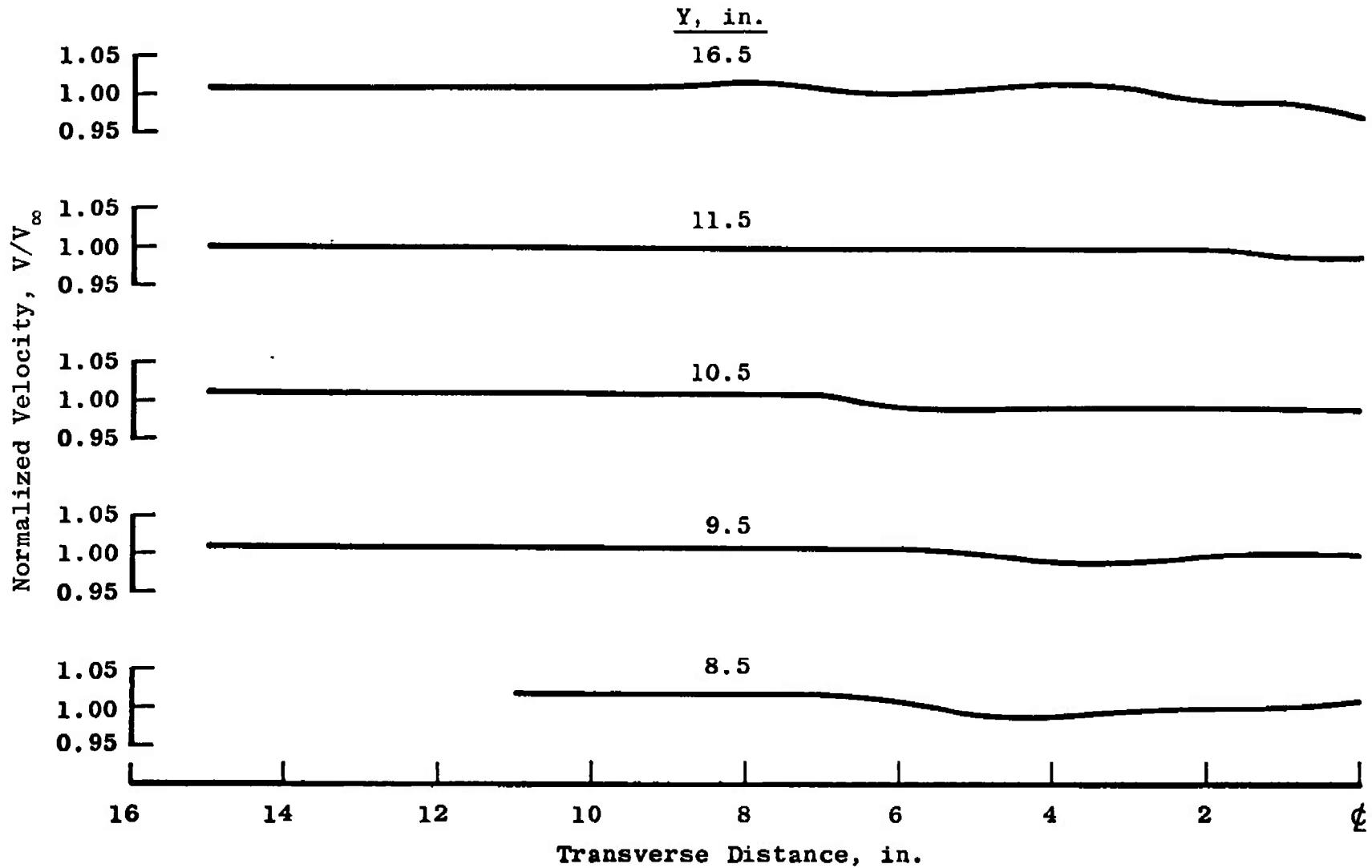


Fig. 10 Concluded

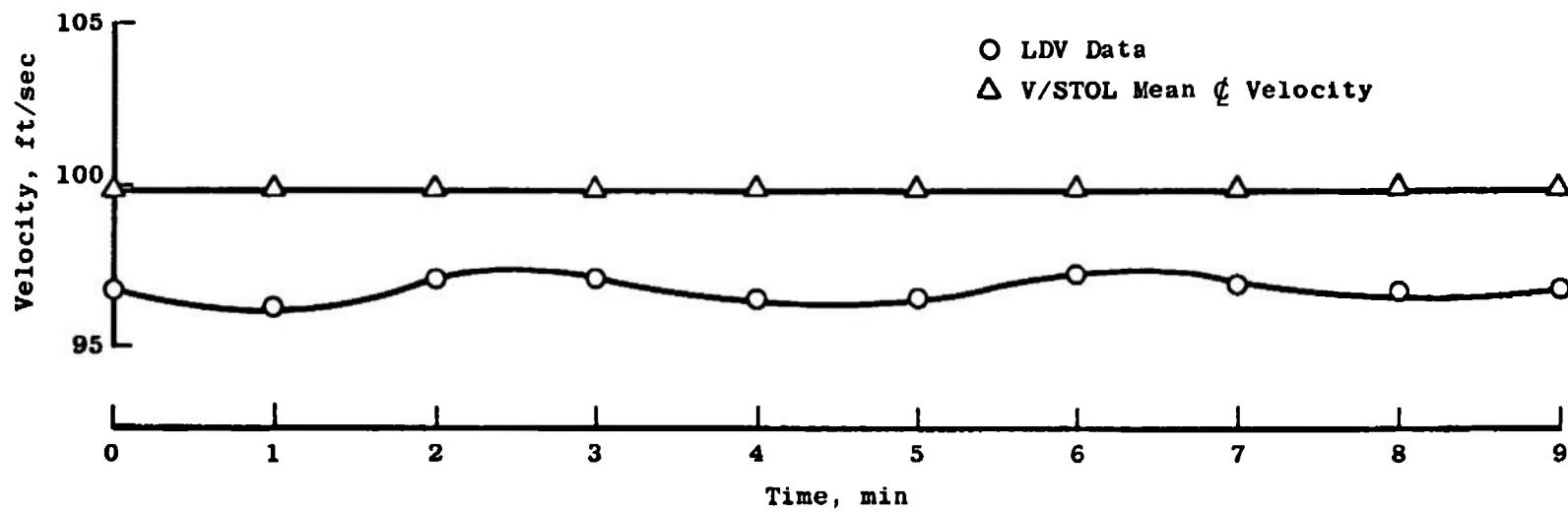


Fig. 11 Sinusoidal Boundary-Layer Velocity Variation

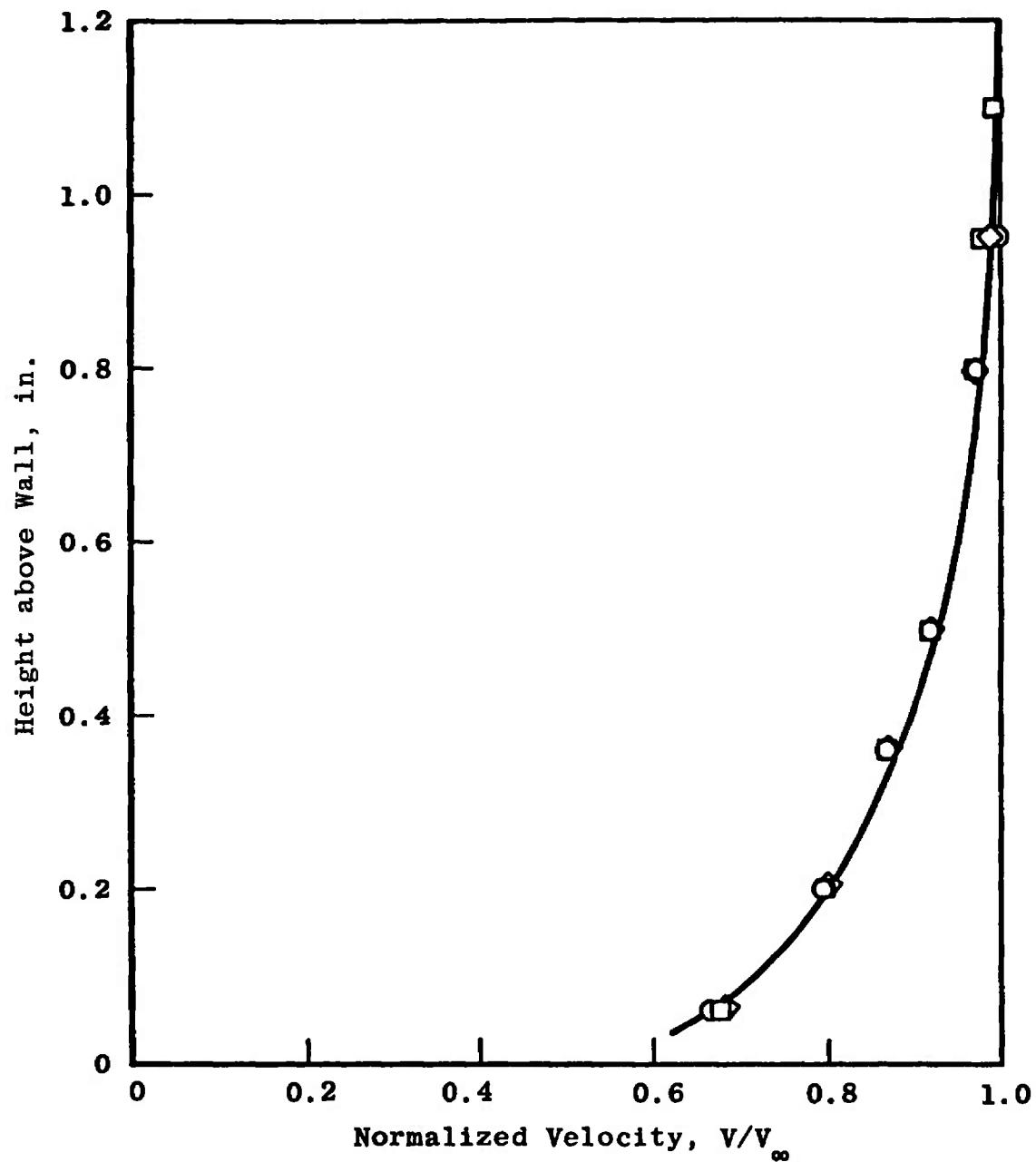


Fig. 12 Boundary-Layer Rake Normalized Velocities

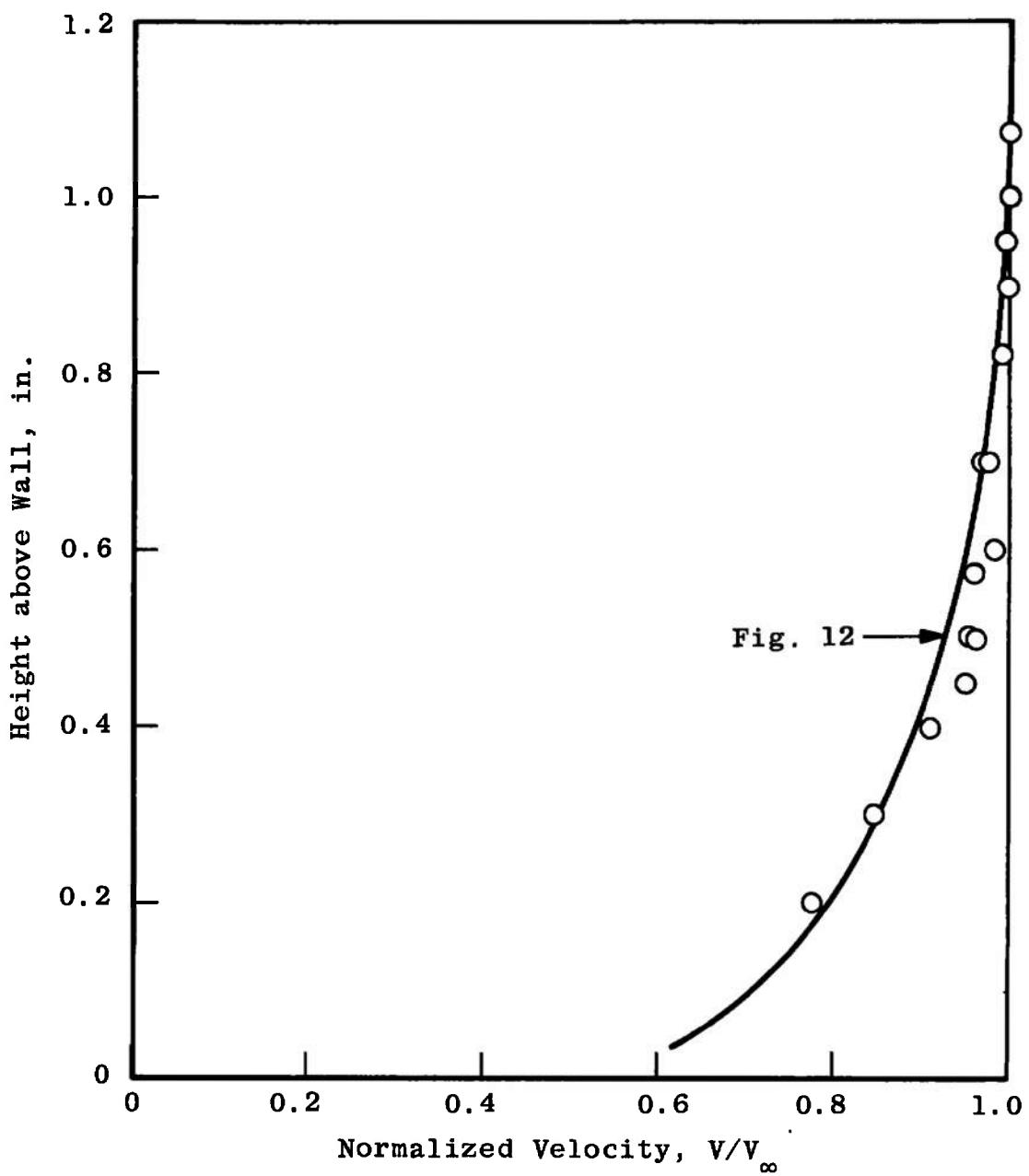


Fig. 13 Normalized Laser Doppler Velocimeter Boundary-Layer Velocities, $V_\infty = 60$ ft/sec

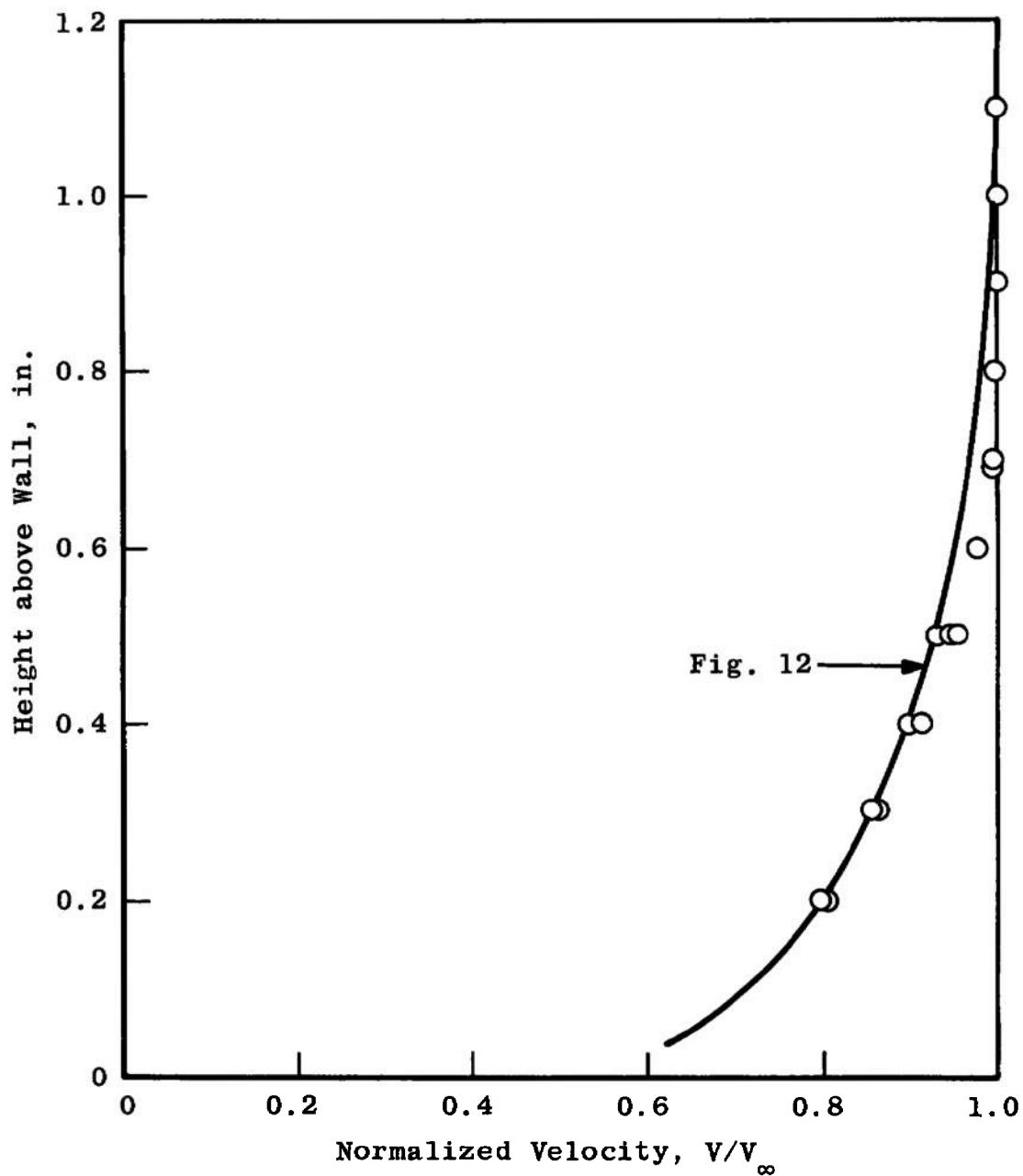


Fig. 14 Normalized Laser Doppler Velocimeter Boundary-Layer Velocities, $V_\infty = 100$ ft/sec

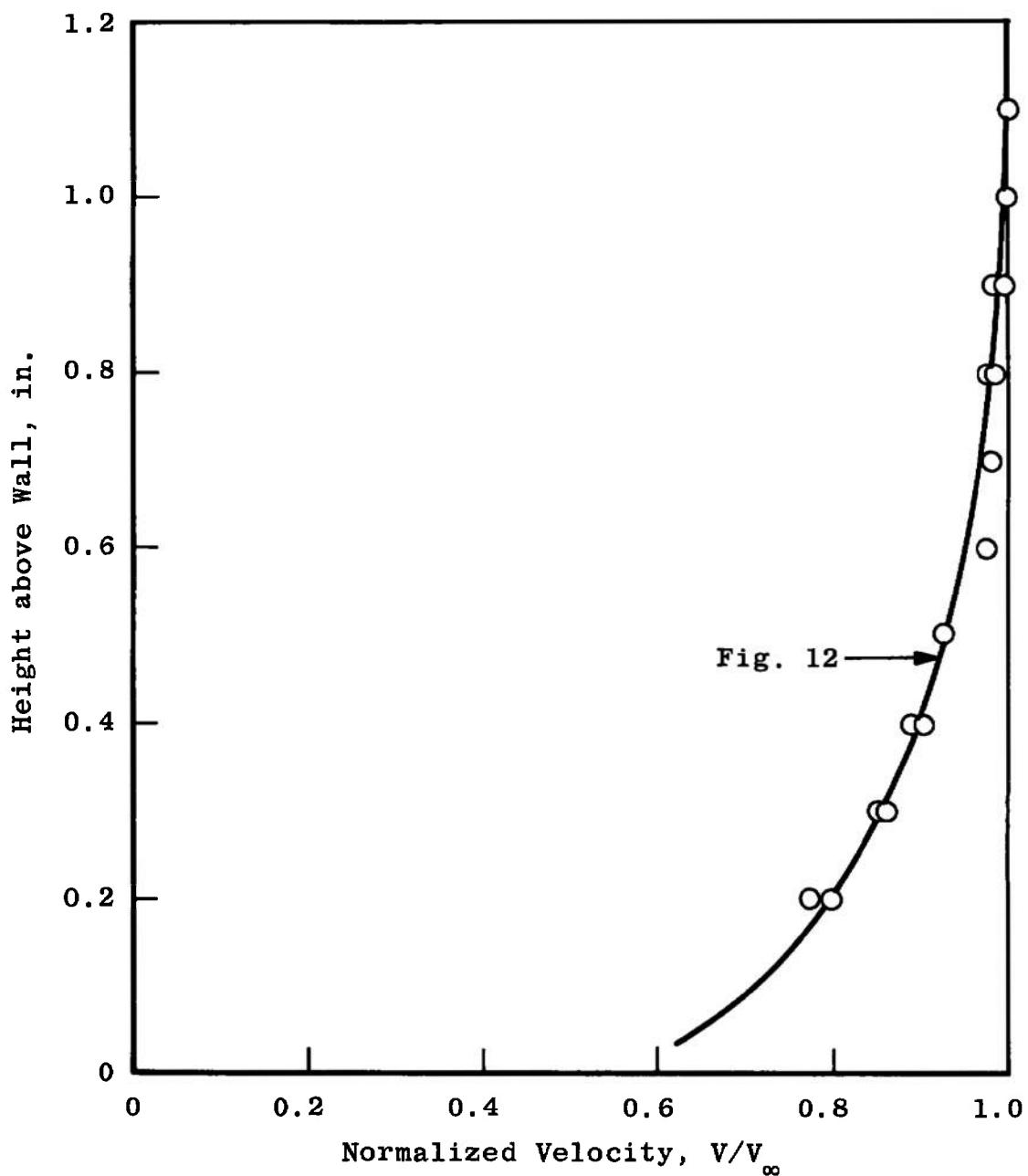


Fig. 15 Normalized Laser Doppler Velocimeter Boundary-Layer Velocities, $V_\infty = 160$ ft/sec

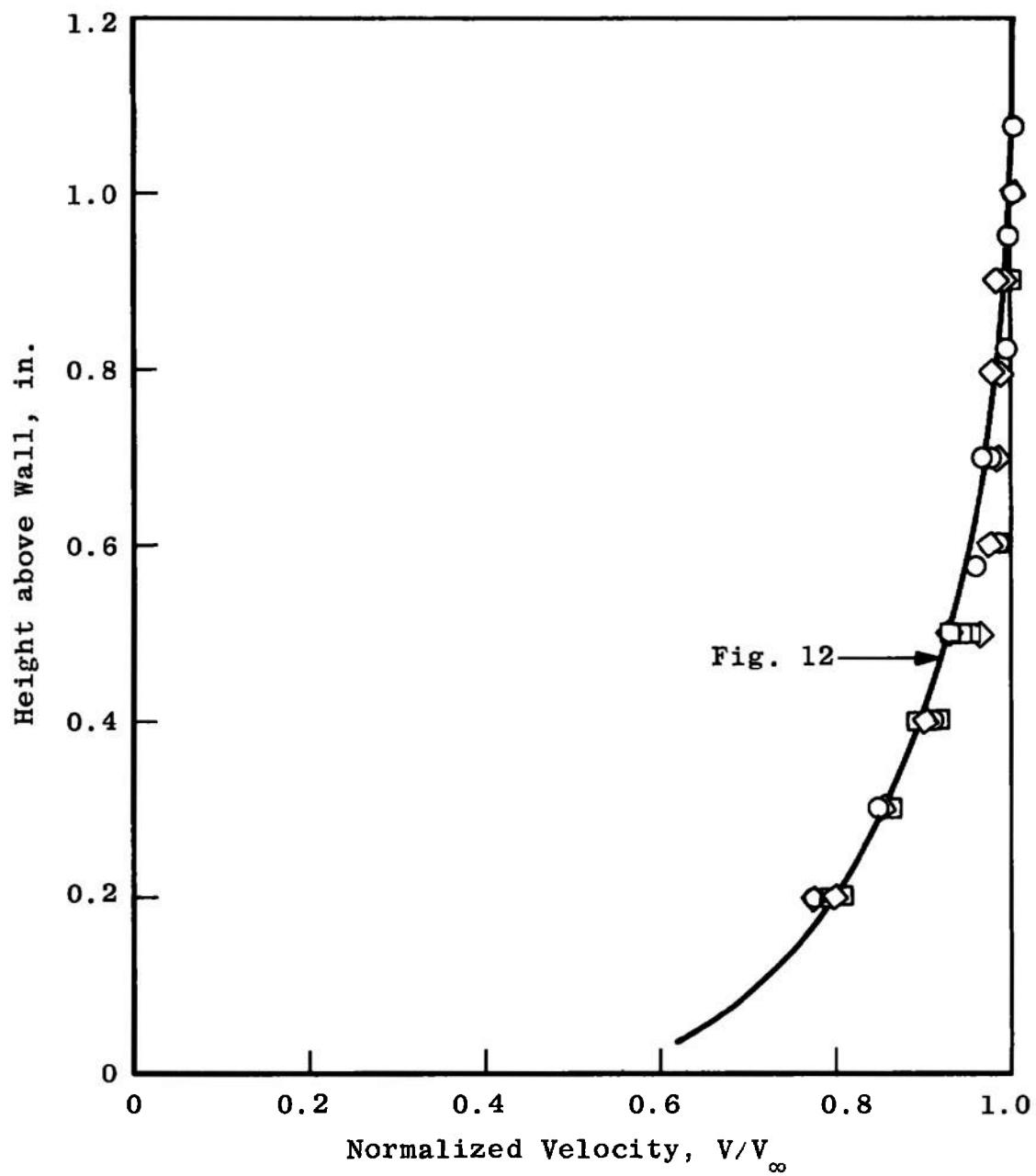


Fig. 16 Combined Laser Doppler Velocimeter Normalized Velocity Data

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